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ON THE CAUSE OF ELECTROTONUS AND OF THE NORMAL FORMULA OF POLAR REACTIONS.

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(*With four wood-cuts.*)

WHEN a motor nerve that has been isolated from its natural bed of superior conducting materials is subjected to the action of either pole of a galvanic battery, a stimulation of its functions is produced when the circuit is closed and opened. It is well known that this stimulation varies in amount at the closure and at the opening, and with the pole that is used. Briefly, it is found that the strongest stimulation is at kathodic closure, and the next strongest at anodic opening, with anodic closure following closely, and kathodic-opening stimulation only produced by the strongest currents. Such is the substance of the normal formula of contraction as ascertained in the laboratory. It corresponds closely with the formula obtained in man, especially when the nerve is not deeply situated.

The well-ascertained facts of electrotonus show that when the isolated nerve is kept under the influence of the kathode of a constant current, any additional stimulus applied to the area directly under that pole will produce a greater contraction than normal; and that when the nerve is under the influence of the anode a parallel lessening of its excitability is found. This has recently been shown to be true of the embedded nerve also, as proven by the experiments of Waller and De Watteville,[1] conducted under a special grant from the Royal Society of England.

A single fact underlies, therefore, both electro-contractility from interrupted currents and electrotonus from constant currents, namely: that the kathodic condition is at least more exciting than the anodic. This preponderance of excitability to the kathode will be recurred to directly.

It is almost unnecessary at the present day to add further to these preliminary statements by saying that the action of a pole has nothing to do with the correspondence, or want of correspondence, between the directions of the electrical current and of the current of nerve force. This assumption of the physiologists, who dealt only with uncovered nerves, in which such a correspondence between the two paths of force could be readily obtained, was disposed of by the fact that experiments on the embedded nerve yielded the same results, though the current traversed the nerve so situated in at least three different directions under the one pole (fig. 1). The conclusion was forced that the stimulation and its varieties were polar effects rather than directional effects of the current, and this view has been generally adopted by writers on the subject. I may here also remind you of an older conclusion of the same investigators that requires constant remembrance, and that is: that an excitation great enough to produce contraction

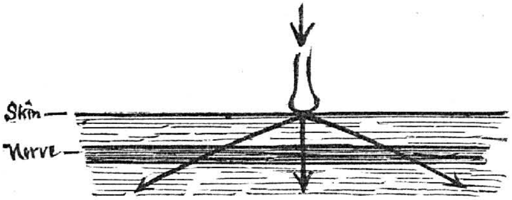

FIG. 1.—Diagram of a nerve under unipolar influence. It is traversed by the current lines in all directions.

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[1] Philosophical Trans., 1882, p. 961.

must be due to a current variation ; and that the variation or oscillation of current must occur within a certain time—in other words, must be sudden. It is true that we have tetanoid contractions during the continuous flow of a strong galvanic current, but these are doubtless due to those minute variations that are now presumed to exist in the most constant current, becoming visible as striæ when such currents are passed through partial vacuums in the dark. These variations, being very numerous and in rapid succession, produce, when the volume of the galvanic current is overpoweringly great, a tonic contraction of the muscle similar to that produced by the rapidly-successive faradic currents.

Electro-contractility is therefore essentially due to the act of current variation. Electrotonus is dependent only upon the period of current flow, and is probably not due to the slight variations just referred to as producing the tetanoid contraction. It is further important to remember that both these actions of contraction and tone are physiological in character, being of a different nature from the chemical or electrolytic action of the current.

With these preliminary remarks I will proceed to a discussion of the electro-physical laws governing these polar effects, and will subsequently present a new theory of their explanation that may or may not be acceptable ; being convinced that these obscure questions of the physiological action of electricity can only become comprehensible through a study of the physical conditions of currents during experiments.

The laws of current diffusion within large conductors have been indicated for years by the necessities of Ohm's law, but no actual determination by experiment was made before the investigations of Prof. W. G. Adams, the results of which are embodied in the Bakerian Lecture for 1875.[1] Buckets and tubs of salt water and various acid solutions were used for the experiments, a continuous galvanic current being sent through these large and variously shaped conductors from poles inserted in them at proper distances apart. During the passage of the current, measurements were made of the potential of various spots in the body of the liquid by means of galvanometer electrodes insulated to the tip. These, being freely movable in any direction, permitted the mapping out of lines of points at which the potential was the same, thus determining the equipotential lines throughout the interior. If one galvanometer electrode was placed at one of these points, no deflection could be obtained with the opposite galvanometer electrode on any spot of the same line; with the opposite galvanometer electrode placed at any other point a deflection would result, indicating the difference between the potential of the two points.

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[1] Proc. Royal Soc., Vol. XXIV., p. 1. See also a theoretical discussion by Foster and Lodge, Proc. Lon. Phys. Soc., Vol. I., p. 113.

These experiments proved what had previously been a mere theory, completely verifying it. The principles thus established are of the utmost importance to medical users of electricity, and I have therefore designed for the use of my classes at the Infirmary some illustrations (figs. 2, 3, and 4) showing the main facts to the eye. The diagrams are all drawn for a current of twenty volts, and show its behavior within conductors of varied thickness; the position of the potentials and lines of flow only being indicated, and no reference being had to the number of milliampères transmitted. The latter would depend on the resistance of the several conductors—a question that we are not now interested in, as the equipotential lines remain the same whatever the volume of the current, and are only dependent on the number of volts in the circuit.

You will notice that a current of twenty volts has a positive potential of ten volts at the anode and a negative potential of ten volts at the kathode. Each potential recedes to zero as the centre of the intervening resistance is approached, the points where certain potentials are found being indicated in the diagrams by dotted lines of equal potential. The current flows from potential to potential in what are called lines of flow, always crossing a potential line at right angles, just as water flows down a series of steps. The theory that prevails at present in the practical literature of electricity, assumes that electrical energy is in a state of accumulation at the anode and deficiency at the kathode,—the anode being at the highest point; zero at the level of the earth; and the kathode at the lowest point of an imaginary incline extending from a certain distance above, to an equal distance below, the level of the earth or equilibrium. The flow is down this incline with an impetus measured by the height of the anode above the kathode.

In the narrow conductor (fig. 2) the equipotential lines, or in illustrative language, the edges of these steps of electric level, extend straight across the conductor, the lines of flow being straight lines from pole to pole. In the wider conductor (fig. 3) the lines of potential tend to curve somewhat about the poles, hence the lines of flow on either side of the centre one, which remains straight, curve a little also, as the potential lines must be crossed at right angles.

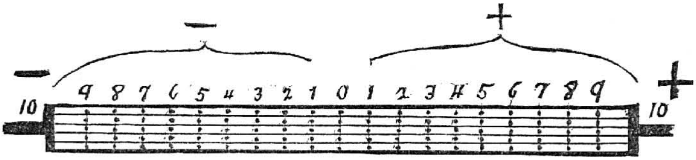

FIG. 2.—Diagram showing the distribution of a current of twenty volts within a narrow conductor. The milliampères are equally distributed in the lines of flow (represented in the cut by horizontal lines). The lines of equal potential (represented in the cut by dotted lines) are drawn one volt apart, and have a value indicated by the figures.

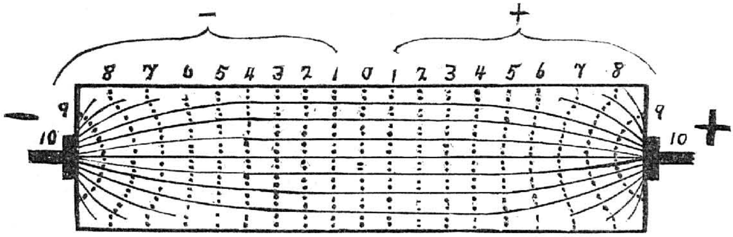

FIG. 3.—Distribution of a current of twenty volts within a wider conductor. The lines of flow on either side of the central one curve somewhat, as do also the most positive and most negative potentials.

When the current is passed through so large a conductor as the human body (fig. 4) the potential lines become arcs of small circle, about each pole, the size of the circles rapidly increasing as we proceed away from the poles. The lines of flow necessarily crossing the potential lines at right angles become variously curved also, those next to the straight line in the centre remaining straightest; while those most distant from the direct line from pole to pole curve the most. Prof. Adams found that all equipotential lines abandoned their regular curves when approaching the edges of the conductor, or the sides of the vessels containing the liquid, and cut them at right angles. This means that the lines of flow nearest the boundaries of a conductor are always parallel to the boundary edges.

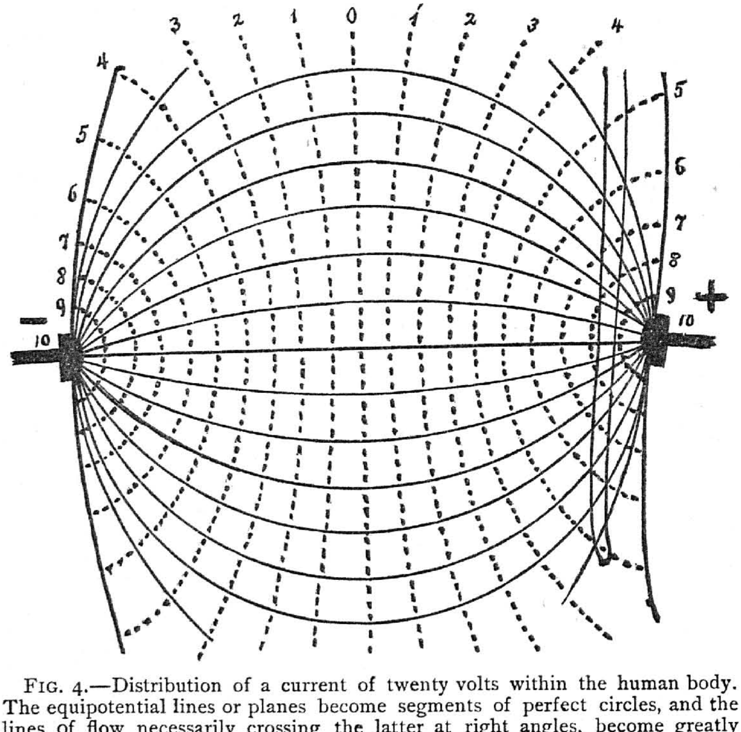

FIG. 4.—Distribution of a current of twenty volts within the human body. The equipotential lines or planes become segments of perfect circles, and the lines of flow necessarily crossing the latter at right angles, become greatly curved, and extend to all parts of the body in passing from pole to pole. The number of milliampères traversing the lines of flow differs somewhat, being inversely proportional to the length of the lines.

When the poles are applied to opposite sides of a large thick conductor like the body the lines of flow curve between them in all directions, to the right and left, upward and downward. Each equipotential is best conceived in the mind, therefore, as a curved plane shaped like the half of a hollow globe, placed with the concavity towards the pole of the same sign. In a model constructed to show this, the material between the planes would resemble thick cups of progressively increasing size and curve, placed in two nests, base to base, and with the smallest cups next to each pole.

It is necessary to add that these diagrams are drawn to represent the distribution in a homogeneous conductor, such as a single organ, and that slight alterations would be required to make them fit any composite conductor made up of the various human organs, differing as they do in conductivity. This would only make the lines of potential and flow more or less wavy, however, the general direction remaining the same; and as no two persons would present the same waviness, the average curve was adopted as represented.

With these facts before us let us examine the theory of polar reactions and electrotonus first promulgated by Helmholtz, and so widely published since by Erb, De Watteville, and others. A cardinal principle of this theory is that the kathodic polarity alone is exciting. On this point the theory is doubtless correct, but the hypothesis resorted to to explain it is somewhat confusing, and I think weakens the force of the main point. I allude to the assumption of a peripolar region of opposite polarity in the neighborhood of each pole. You are probably all familiar with the diagrams used to convey this idea. I have been unable to find any support for this theory outside the works of medical writers. The diagrams described in this paper show nothing of the sort. It will be seen by again referring to the latter that the potentials of either sign gradually lessen from the points of entrance to the region midway between them, where it is zero. The exact situation of zero, or the point of no potential, depends upon the evenness of the resistance of the body—it is at the middle of the resistance. Of course, any one point among the positive potentials is relatively negative to a higher potential, and conversely with the negative points; but no reasoning should assume that a positive potential is absolutely negative merely because it is less positive than a point higher up in the scale. All positive potentials are more positive, and all negative potentials are more negative, than the general body condition, which is nearer equilibrium.

The peripolar theory probably arose through the mistake of regarding the lines of flow through a nerve instead of considering the potential to which it is subjected. It was argued that if the current lines passed through a nerve their entrance at one side created an anodic polar region, and their exit from it at the other side created a kathodic peripolar region—both regions being within the diameter of the nerve. This view of the matter is seen to be faulty when you glance at fig. 4, where the cord is shown bathed in one polarity; with a potential stronger on the nearer side it is true, yet showing at the most a mere gradation of one kind. Moreover, the entrance of a line of flow into a nerve and its exit from it are not separate facts but parts of one fact, and therefore incapable of presenting the current variation essential to the production of a contraction.

It seems to the writer very difficult for the average mind to grasp these questions of the polar reactions and their rational explanations unless the deep meanings of electrotonus are clearly apprehended. That electrotonus is a physiological impression made upon a nerve, which, besides altering the nerve excitability during its continuance, will give rise to a contraction if the impression is suddenly produced or suddenly ended, is now well established. Regarded in this way, katelectrotonus, producing a heightened excitability during its continuance, causes a very great contraction at its inception and a very slight contraction at its cessation. Anelectrotonus, producing a lessened excitability during its continuance, causes a slight contraction at its inception and a great contraction at its cessation.

It is thus seen that all alterations of the electric equilibrium of the nerve will produce contractions—provided the alterations are great enough,—as has been understood for many years; and the rational cause can well be conceived to be the mere fact of some sort of molecular change accompanying the change of potential; but who has explained why katelectrotonus will increase irritability and anelectrotonus lessen it, or why the production of katelectrotonus causes a greater contraction than its cessation, while the cessation of anelectrotonus causes a greater contraction than its production? Why, in other words, the positive pole is the most negative in its action on the body? I am not aware that this question, important as it must be, has ever been formulated before. A possible answer occurred to the writer some months ago after reading a suggestive paper[1] in an English physical journal. This paper contained an elaborate citation of facts and observations to prove that the direction of electrical flow is the reverse of that now held, being from the kathode to the anode. The kathode, accordingly, is the true plus pole, or pole of raised level, and the anode the true minus pole, or pole of depressed level. Using the convenient phraseology of physical electricians, the kathode becomes the "source" of supply to the body, and the anode the "sink."

The English observer's facts were all connected with the physical behavior of electricity of very great potential, as produced by Holtz machines, and no reference was made to the action of the poles on living tissue; yet no individual fact could bring stronger evidence in support of this theory. Adopting that theory, the laws of physical electricity remain the same, with a mere change in the method of expression—in fact, a mere change of terms. With its aid both electrotonus and the polar reactions become easily and rationally explainable. Katelectrotonus is a condition of increased excitability, because the normal potential of the nerve is exalted. Anelectrotonus is a condition of depressed excitability, because the normal potential is depressed. The sudden raising of the potential of the nerve above equilibrium (kathodic closure) produces the greatest contraction; while its fall to equilibrium (kathodic opening) produces the least. The sudden depression of the potential of the nerve below equilibrium (anodic closure) produces also a small contraction, and the sudden restoration of the depressed potential to equilibrium (anodic opening) produces a contraction that is next to the greatest.

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[1] The paper referred to in the text was only casually read by the present writer while pursuing another line of search in a library. Its reference was taken for more careful perusal, but the note-book containing it was lost, and subsequent search has failed to rediscover the paper. It is interesting to note that the *London Lancet* for May 1, 1886, contains an abstract of the Lumleian Lecture delivered since the present paper was written, in which a paragraph occurs referring to the uncertainty of current direction, but making no suggestions.

In other words, kathodic closure is in this theory the sudden application of electric energy to the part, and anodic closure is the sudden abstraction of electric energy from it. At kathodic opening the energy applied at kathodic closure is permitted to dissipate; while at anodic opening the vacuum produced at anodic closure is suddenly annihilated by the inward rush of the more normal potential of the surrounding tissues.

It may therefore be noted that a sudden application of this energy, or rise of potential, is a greater excitant than a sudden abstraction of the energy, or fall of potential—a fact that seems quite a matter of course. Additionally, if the rise is from equilibrium upwards, the excitation is greater than if it is from a depressed potential to equilibrium only; and if the depression is from equilibrium downwards, the excitation is greater than if it is from an exalted potential to equilibrium only.

The discussion of this subject could be carried much further with advantage, but I think sufficient has been said to show that the new theory, if once established, would be of great advantage in making comprehensible what is now merely a bare collection of facts.